

Radiometric calibration status of Landsat-7 and Landsat-5

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ABSTRACT

Launched in April 1999, Landsat-7 ETM+ continues to acquire data globally. The Scan Line Corrector in failure in 2003 has affected ground coverage and the recent switch to Bumper Mode operations in April 2007 has degraded the internal geometric accuracy of the data, but the radiometry has been unaffected. The best of the three on-board calibrators for the reflective bands, the Full Aperture Solar Calibrator, has indicated slow changes in the ETM+, but this is believed to be due to contamination on the panel rather than instrument degradation. The Internal Calibrator lamp 2, though it has not been used regularly throughout the whole mission, indicates smaller changes than the FASC since 2003. The changes indicated by lamp 2 are only statistically significant in band 1, circa 0.3% per year, and may be lamp as opposed to instrument degradations. Regular observations of desert targets in the Saharan and Arabian deserts indicate the no change in the ETM+ reflective band response, though the uncertainty is larger and does not preclude the small changes indicated by lamp 2. The thermal band continues to be stable and well-calibrated since an offset error was corrected in late-2000.

Launched in 1984, Landsat-5 TM also continues to acquire global data; though without the benefit of an on-board recorder, data can only be acquired where a ground station is within range. Historically, the calibration of the TM reflective bands has used an onboard calibration system with multiple lamps. The calibration procedure for the TM reflective bands was updated in 2003 based on the best estimate at the time, using only one of the three lamps and a cross-calibration with Landsat-7 ETM+. Since then, the Saharan desert sites have been used to validate this calibration model. Problems were found with the lamp based model of up to 13% in band 1. Using the Saharan data, a new model was developed and implemented in the US processing system in April 2007. The TM thermal band was found to have a calibration offset error of 0.092 W/m² sr μm (0.68K at 300K) based on vicarious calibration data between 1999 and 2006. The offset error was corrected in the US processing system on April 2007 for all data acquired since April 1999.

Keywords: Landsat, ETM+, TM, radiometry, calibration

1. INTRODUCTION

The Landsat instruments, the Thematic Mapper (TM) and the Enhanced Thematic Mapper Plus (ETM+), have been acquiring coverage of the earth's surface since 1984. Landsat-7 was launched in April 1999 and its ETM+ sensor has been used to acquire data nearly continuously since July 1999. The ETM+ has 6 reflective spectral bands with 30 meter spatial resolution: Band 1, 0.452 - 0.514 μm; Band 2, 0.519 - 0.601 μm; Band 3, 0.631 - 0.692 μm; Band 4, 0.772 - 0.898 μm; Band 5, 1.547 - 1.748 μm; and Band 7, 2.065 - 2.346 μm; one panchromatic band (Band 8; 0.515 - 0.896 μm) at 15 meter spatial resolution and one 60 meter thermal band (Band 6; 10.31- 12.36 μm). This scanner uses silicon detectors on an uncooled focal plane for Bands 1-4 and 8; InSb detectors for Bands 5 and 7 and HgCdTe detectors for Band 6 on a 91K radiatively cooled focal plane. Two gain states are available for each band; the high gain state is 1.5 times higher than low gain state in the reflective bands. The data are quantized to 8 bits. The scan-line corrector mirror assembly stopped working in 2003, which affects the spatial coverage of the scanner, but has not affected the radiometric performance¹. In 2007, the scan mirror and shutter flag were unable to maintain synchronization and the instrument was switched to an alternate scanning mode, called Bumper Mode (BM). This also has affected the geometric performance of ETM+ but not the radiometry.

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Landsat-5 launched in 1984 and the Thematic Mapper (TM) has been operating for well over its predicted lifespan of three years. Privately run for most of its lifetime, the spacecraft and the data archive reverted to government control in 2001. The TM has a similar suite of bands as the ETM+, though TM does not have a panchromatic band and the spatial resolution of the thermal band is 120 meters. The instrument only has one gain state and the data are quantized to 8 bits. A technical failure of one of the transmitters in 1987 means that only data acquired within an acquisition circle of a ground station can be downlinked. The US archive, therefore, primarily contains data acquired over North America. However, international ground stations hold years of global TM data as well. The TM scanner was switched to BM in 2002. It also has not affected the radiometric performance of the instrument.

2. ONBOARD CALIBRATION

2.1 ETM+

The ETM+ has three onboard calibration systems for the reflective bands: the Internal Calibrator (IC), the Partial Solar Aperture Calibrator (PASC), and the Full Aperture Solar Calibrator (FASC)². The IC and FASC continue to provide useful calibration data, but the PASC is saturated in most bands so will not be discussed here.

The ETM+ IC consists of two lamps, a calibration shutter flag that oscillates in synchronization with the scan mirror, and a set of optics that pipes the light from the lamp to the shutter flag. The shutter blocks the earth view from the focal plane while the scan mirror is turning around and provides the detectors with a dark background and a bright pulse from one of the lamps. The dark region is used to measure the offset of the detectors for each scan and the lamp pulse gives a measure of the gain of the detectors. The lamps are used one at a time, but one of the lamps is on for every scan of the mirror. Lamp 1 has been on for nearly all the data acquisitions since launch, while lamp 2 has only been used regularly since 2003 and since then only approximately twice per month. The band-average system gains as calculated from the IC are presented in Figure 1 illustrating the behavior of the two lamps since launch; a representative sample of the bands is shown. These data are filtered to limit the instrument on-time to between 5 and 15 minutes, as the lamps exhibit a slow increase in output while warming up and, once warmed, a small decrease in output. System response to lamp 1 has changed dramatically since launch in all bands, with most of the change occurring in the first few years. None of the other calibration systems show this much change, so the change is most likely in the IC system. Lamp 2 is showing a slow degradation since being used more regularly, but it is not unexpected based on lamp 1 trends. The lamp 2 change is statistically significant in bands 1 and 2, but is less than 0.25% per year.

The IC also serves as the only onboard calibration system for the thermal band³. The shutter flag has on it a toroidal mirror, which reflects radiation from a conical blackbody onto the optics and through to the cooled focal plane. The non-mirror part of the shutter is coated with a high-emissivity paint and sits at the instrument ambient temperature. Outputs from thermistors monitoring the temperatures of some components within ETM+ are included in the downlinked data. The instrument gain is calculated from the shutter and blackbody radiance and temperature. The instrument offset model, developed during prelaunch testing, is calculated from the shutter and several other instrument components which radiate into the optical path. Figure 2 shows the band 6 instrument gain and offset. The gain may be changing at less than 0.1%, per year and the offset at 0.27% per year over the lifetime of the mission. The prelaunch gains are still used in the processing system for calibration, but the IC calculated offset is used so the offset changes are being accounted for.

The FASC is a diffuser panel mounted outside the entrance aperture of the ETM+. Approximately monthly, the panel is commanded to move in front of the aperture while the spacecraft is emerging from solar eclipse, and reflects the rising sun onto the focal plane. Using prelaunch measured reflectance factors for this panel, combined with orientation information and solar illumination angles and solar spectral irradiance values, the FASC can provide an absolute calibration of the ETM+ instrument. FASC-determined instrument gains are also shown in Figure 1. The response to the panel is dropping over time in most bands. A contaminant is thought to be depositing unevenly on the panel, degrading the surface non-uniformly across its width. The gains shown here are calculated from the cleanest portion of the panel, though it appears that even the cleanest region is degrading over time.

2.2 TM

The TM IC system is similar to the ETM+ IC consisting of a shutter flag and lamps, though TM has three lamps instead of two⁴. The three lamps are cycled through a regular on/off pattern such that there are a total of eight combinations of lamp intensities (lamp states). During a 24 second scene, each lamp state is seen once. The original calibration method involved regressing the eight lamp state signals against their prelaunch measured radiances to estimate the system gain

and offset. However, the three lamps have decayed differently over time, and it was clear to the calibration team in 2001 that the regression-calculated gain did not represent the true instrument gain. A model was developed based on the most well behaved lamp, removing what was thought to be only lamp decay and accounting for all presumed instrument decay for all bands. The exponential+constant model was implemented in the USGS processing system in May 2003 as a daily gain look-up table (referred to as LUT03). Figure 3 shows the regression-based gain along with the LUT03 model that replaced it for representative bands. Regression gains are only shown through about 17 years since launch (YSL) as synchronization problems made it difficult to accurately find the lamp pulses after that. The LUT03 model was scaled to the ETM+ cross-calibration point (discussed later), so do not necessarily overlap with the regression gains or start at the prelaunch estimated gain. A build-up of an ice on the dewar window of the cold focal plane affects the responsivity of bands 5 and 7⁵. The containment causes an interference effect leading to cyclic variations in the signal. This is apparent in Figure 3, by the oscillation of the gain in band 5.

The TM has the same IC system for calibration of the thermal band as the ETM+. However, the prelaunch model for the offset calculation only considers the shutter radiance; no other components were included in the model⁶. Instead, three constants were determined to account for the offset of the instrument. The thermal band is affected by the build-up of ice on the dewar window, but differently than in bands 5 and 7. The contaminant attenuates the incoming signal, so the responsivity of the band drops as the layer builds. When an outgassing is performed, the ice layer is removed and the band returns to maximum responsivity. Figure 4 illustrates the instrument gain and offset, clearly showing the effect of the contaminant. The gain and offset of the band are constantly degrading but these changes are accounted for in the calibration of the data.

3. TM CROSS-CALIBRATION WITH ETM+

During the on-orbit verification of the ETM+, the Landsat-7 spacecraft was placed in an orbit such that TM and ETM+ flew in tandem for three days imaging the same sites within 15 minutes of each other⁷. The data collected during this period is the single most accurate absolute calibration data point for TM. The point is shown on all the TM plots and was the absolute tie point for the 2003 TM calibration update.

4. VICARIOUS CALIBRATION

Teams from the University of Arizona (UA) and South Dakota State University (SDSU) have performed regular vicarious calibration of the ETM+ and TM reflective bands⁸. UA works primarily at Railroad Valley, Nevada (RRV) and Ivanpah Playa, California. SDSU works primarily at a large vegetated field in Brookings, South Dakota. Details vary between the two teams' techniques but the basic methodology involves measuring the surface reflectance and atmospheric properties at the time of the Landsat overpass and propagating the signal from the Sun through the atmosphere, reflected off the target and back through the atmosphere to the sensor. The predicted exoatmospheric radiances are converted to gain using the measured instrument response in DN and are shown in Figures 5 for ETM+ and Figures 6 for TM. The precision or reproducibility of these measurements under good atmospheric conditions is on the order of 2-3% (1-sigma).

Rochester Institute of Technology (RIT) and NASA/Jet Propulsion Laboratory (JPL) perform regular vicarious calibration of the ETM+ thermal band. RIT works on Lakes Ontario and Erie and some small bays and lakes in the Rochester area⁹. JPL has permanent radiometers on Lake Tahoe and the Salton Sea¹⁰ but has also taken measurements on hot playas. Again, the details vary but the measurements involve measuring the surface-leaving radiance or surface temperature, propagating the signal through the atmosphere and predicting the sensor-reaching radiance. The predicted sensor-reaching radiance is compared to the radiance measured by the instrument. These comparisons are shown in Figure 7 (ETM+) and Figure 8 (TM). The teams found an offset error in the ETM+ thermal band early in life. This was corrected for in the processing system in 2001. For the TM thermal band, an offset error was being tracked and was finally corrected for in April 2007.

5. DESERT SITES

In an attempt to separate degradation of the onboard calibration systems from ETM+ instrument degradation and to supplement the vicarious calibrations, several Saharan and Arabian desert sites were chosen for routine acquisition and processing. The four sites picked were a subset of regions selected in a separate study characterizing the most stable regions of these deserts¹¹ (Table 1). For every cloud-free acquisition of each site, a common 3000x3000 pixel area was selected based on the scene center coordinates. The data were radiometrically calibrated using the current calibration

parameter file coefficients. The band-averaged radiances were converted to exoatmospheric reflectance using the scene center solar zenith angle, daily Earth-Sun distance from the Astronomical Almanac and exoatmospheric solar irradiances from the Landsat Science Data Users Handbook¹². The resulting reflectances were regressed against solar zenith angle and a linear adjustment for any remaining illumination angle dependence due to bidirectional reflectance or other effects was performed. These reflectances were then scaled to gain units to put them on the same scale as the other calibration sources, though they do not inherently contain any absolute calibration information. Figure 9 shows these rescaled reflectances for the four sites. The sites are treated separately in the analysis and an average is taken of the resulting change estimates. The trends from these four sites are indicating no statistically significant change since launch in the ETM+ gain.

Because of data downlink limitations of the TM, the US data archive contains very few acquisitions of the sites used in the ETM+ study. An attempt was made to instead use the driest location in North America, a portion of the Sonoran desert just across the border from Yuma, Arizona known as the Altar desert (Table 1). While this site is not as stable as the Saharan and Arabian sites, a similar methodology was used to establish a record of instrument stability¹³. The data was not as clean as the ETM+ desert site data, but it provided evidence that the 2003 model was not properly accounting for the early degradation of the TM. As a result, the effort was made to acquire the Saharan scenes from the European archive, which includes northern Africa in its acquisition circle. Only one of the sites used for ETM+ was available in the European archive and the European Space Agency generously provided data of that site, approximately two scenes per year for 20 years. Several more scenes were purchased from Eurimage to fill in a few holes in the data record. Because the lack of confidence in the IC calibration at the time the study was started, raw data were used rather than radiometrically calibrated data as was used for ETM+. The processing steps were the same, and so, though the final output was “gain”, it actually represented a scaled raw DN, with the effects of the earth-sun distance and solar zenith angle removed. The data were scaled to the cross-calibration gain to put them on the same scale as the other calibration sources (Figure 10). Because band 5 was saturated in nearly every acquisition of the Saharan site, the Altar desert results were used instead for band 5 only.

Table 1. Desert Sites used for Calibration Trending

Instrument Analysis	Location	WRS Path/Row	Site Name ¹¹	Latitude	Longitude
ETM+	Egypt/Sudan	177/45	Sudan 1	21.7N	28.2 E
ETM+	Mauritania	201/46	Mauritania 1/2	20.2N	9.2W
ETM+	Saudi Arabia	165/47	Arabia 1	18.8N	46.1E
ETM+, TM	Libya	181/40	Libya 4	28.9N	23.8E
TM	Mexico	38/38		31.7 N	114.5 W

6. DISCUSSION

6.1 ETM+ reflective bands

Figure 11 shows the slopes of the most trusted calibration sources, lamp 2, FASC, and desert sites for all bands. In most bands, the FASC results have the highest precision, but are clearly different from the lamp and desert site results. This supports the hypothesis that even the cleanest portion of the panel is experiencing some degradation and the FASC trends primarily represent diffuser degradation. The lamp results show the largest change in the shortest wavelength, an effect that could be either lamp or instrument caused. These changes, were they real changes in instrument responsivity, could only be occurring at the focal plane as the IC’s signal is inserted into the optical path immediately in front of the primary

focal plane. It is likely that the decreases of 0.1 to 0.3% per year in the infrequently used lamp 2 are at least in part lamp related, since even larger decreases per year are seen in the constantly used lamp 1 IC results. This is consistent with the acceptance of the null hypothesis of zero change with time for trends of the four desert sites. The uncertainty in the percent change per year on the average slope of the four sites is on the same order as the lamp 2 IC trends, namely, less than $\pm 0.3\%$ per year.

The vicarious calibration results are not used here to evaluate trends in the radiometric calibration but are used as an estimate of the accuracy of the radiometric calibration of the ETM+. Table 2 provides average vicarious

Table 2. Percent difference between UA site average gain and current operational model (prelaunch gains).

	RRV	Ivanpah
Band 1	2.7	4.4
Band 2	2.6	4.4
Band 3	0.5	1.7
Band 4	-0.8	-0.2
Band 5	2.5	2.6
Band 7	2.1	2.2

calibration results from UA versus the current operational calibration and indicate that the ETM+ calibration is accurate to within 5%.

6.2 ETM+ thermal band

The vicarious calibration results revealed an error in the ETM+ offset shortly after launch³. This was corrected by modifying one of the prelaunch determined coefficients in the calibration parameter file in December 2001. Since then, the vicarious results continue to suggest the system is calibrated to within $\pm 0.6K$ (see Figure 6).

6.3 TM reflective bands

With the desert site analysis contradicting the LUT03 calibration model, a more rigorous analysis was performed to develop a new model for the TM reflective bands using all of the available calibration sources, including prelaunch, IC, cross-calibration with ETM+, vicarious measurements and desert sites¹⁴. In bands 1-3, the final model is still in the exponential+constant form but with a longer time constant. In bands 4-7, the desert data do not support an exponential decay soon after launch, so the exponential coefficients have been zeroed out leaving only a constant term. The gain model for all bands is:

$$G(t) = a_0 \exp(a_1(t - 1984.2082)) + a_2 \quad (1)$$

where t is time in decimal years and a_n are the new model coefficients given in Table 3. The model agrees within 4% of all of the calibration sources except the IC. The largest changes between the new and old models are in band 1, where the gain was changed by as much as 13% in the first year of operations. Bands 5 and 7 model gains need to be modified by the outgassing model to account for the periodic cycling of the gain. A new daily gain look-up table (LUT07) for TM calibration replaced LUT03 in the processing system in April 2007¹⁵ (Figure 10).

Table 3. Model Parameters for exponential+constant gain model, implemented in the processing system in April 2007 as a daily gain value look-up table (LUT07).

Model Parameters			
Band	a_1	a_2	a_3
1	0.2901	0.1399	1.209
2	0.1246	0.1045	0.63
3	0.0839	0.2386	0.903
4	0	0	1.082
5	0	0	7.944
7	0	0	14.52

6.4 TM thermal band

While the internal calibrator has not indicated any unexpected changes in the responsivity since reverting to government control, an offset error of $0.092 \text{ W/m}^2 \text{ sr } \mu\text{m}$ ($0.68K$ at $300K$) was detected by the vicarious calibration teams⁶. Since the vicarious measurements only go back to 1999, it is not clear if the offset changed during the lifetime of the mission or if this calibration error has been in the system since launch. The offset error was corrected in April 2007 by adjusting one of the calibration coefficients within the processing system, but only for data acquired since April 1999 (the beginning of the vicarious calibration record). The corrected data is now calibrated to within $\pm 0.7K$ (RMS).

7. SUMMARY AND CONCLUSIONS

Landsat-7 ETM+ continues to be a very stable instrument, with the ability to assess its stability limited by the stability of its onboard calibration devices. The use of vicarious calibration and stable desert sites also have limitations that are primarily related to their lower precision and lack of control over atmospheric conditions and/or the inability to perfectly correct for the atmospheric conditions. The onboard calibrators have high precision but as yet uncorrected systematic errors, which leads to the current best estimates of less than 0.5% change per year for all ETM+ reflective bands. The thermal band continues to be stable to $\pm 0.7K$ (RMS) over the lifetime of the instrument.

The evidence presented by the stable desert sites lead to an update of the calibration for the reflective bands of Landsat-5 TM in 2007 for the whole lifetime of the instrument. The previous gain look-up table was replaced with a new one, effectively changing the calibration of some bands by as much as 13% early in life. The new gain model is based primarily on the desert site data, but agrees with the other calibrators within a few percent in all bands. An error in the TM thermal band offset was detected by the vicarious calibration efforts from 1999-2007. This was corrected by adjusting a calibration parameter in the processing system in 2007. With this correction, the thermal band is believed to be calibrated to within $\pm 0.7K$ (RMS) for data acquired since 1999. The state of the thermal band calibration between 1985 and 1999 is unknown; no changes have been recommended for data acquired during those years.

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FIGURES

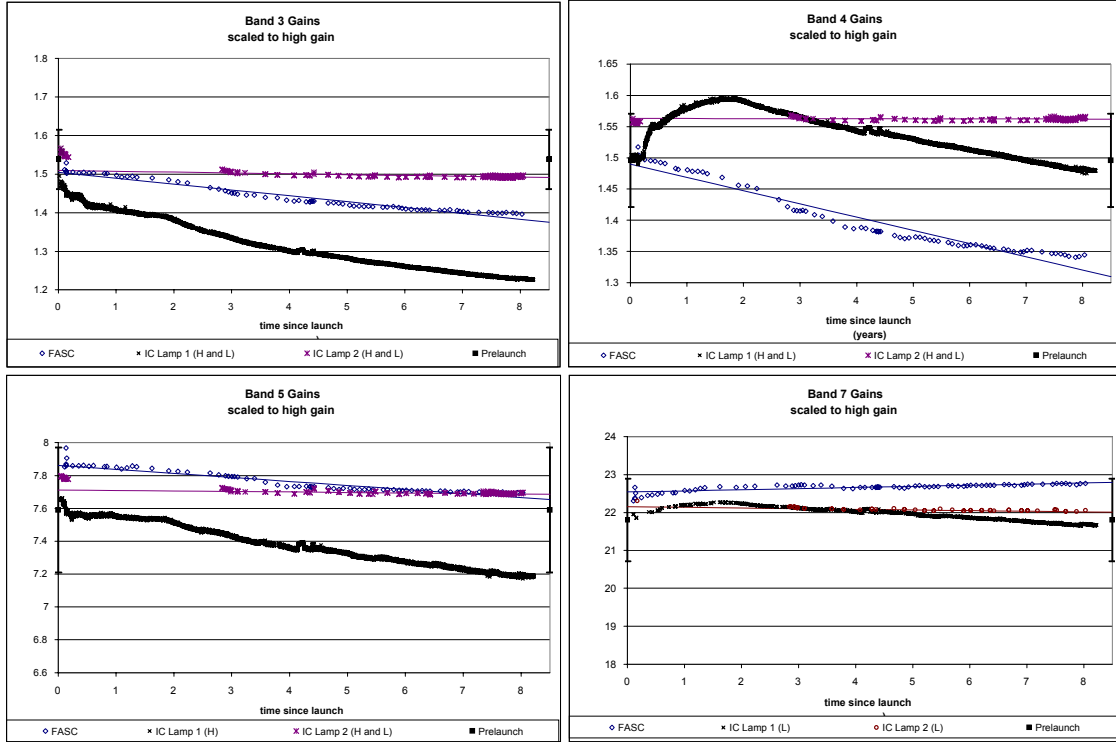


Figure 1. ETM+ onboard calibration devices, IC and FASC, derived, band-averaged gains. IC Lamp data are filtered to only include pulses acquired when the lamps have been on for between 5 and 15 minutes. The prelaunch gain estimates are plotted with $\pm 5\%$ error bars. The FASC data are taken from the cleanest portion of the panel.

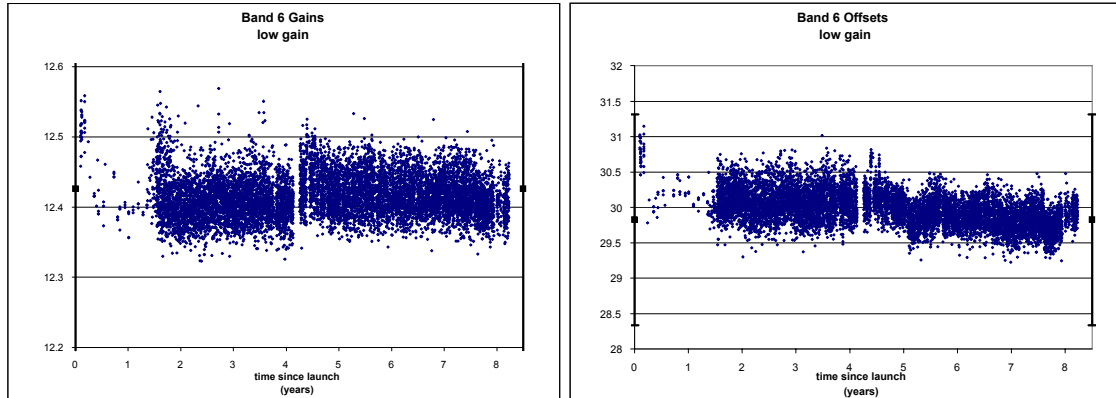


Figure 2. ETM+ thermal band IC derived, band-averaged gains and offsets. Early data processed before the offset correction have been removed, along with other data that was acquired while the instrument was operating outside of its normal temperature range.

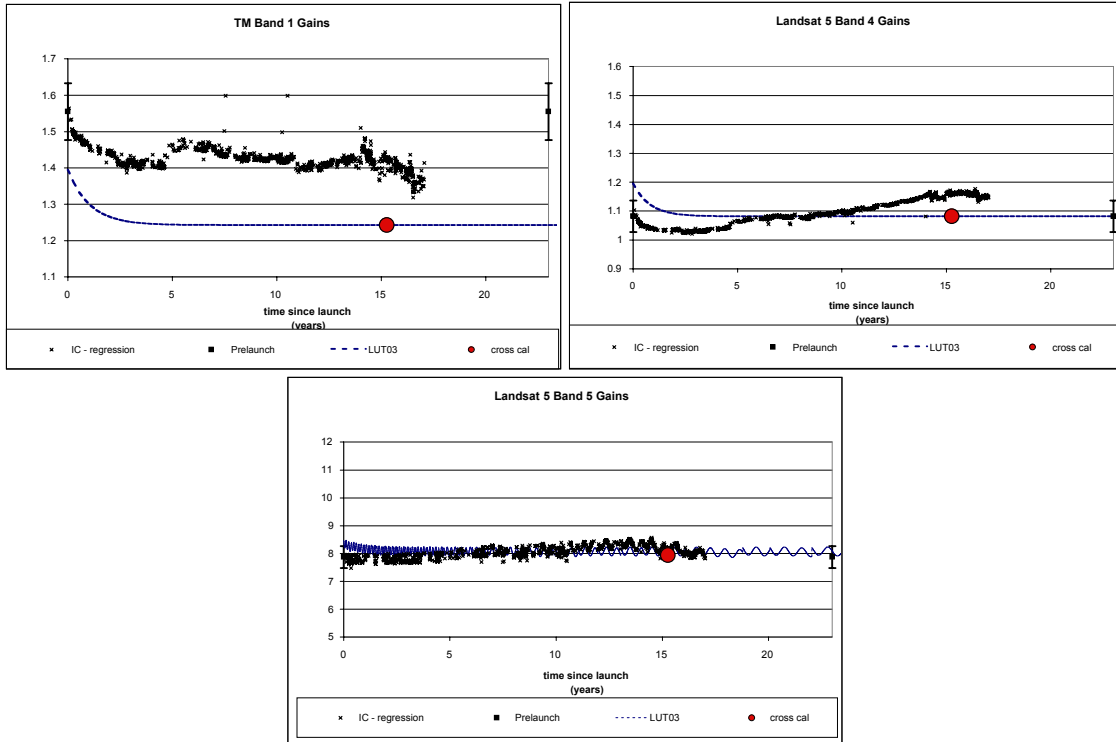


Figure 3. TM internal calibrator derived regression based gains, through about 17 years since launch, along with the lamp model based gains that replaced them in 2003. The prelaunch gains are shown with $\pm 5\%$ error bars. The 2003 model was scaled to the ETM+ cross-calibration in 2000, rather than the prelaunch gains, so the model does not necessarily pass through the prelaunch point.

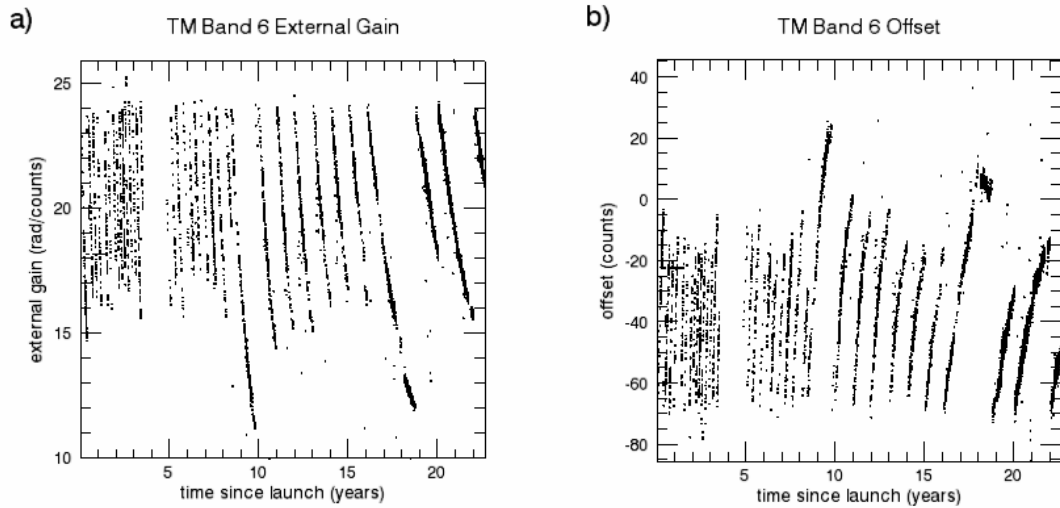


Figure 4. TM thermal band IC derived, band-averaged gains and offsets. The responsivity drops slowly as a contaminant deposits on the window to the cold focal plane. As soon as the layer is melted off, the gain returns to its maximum level.

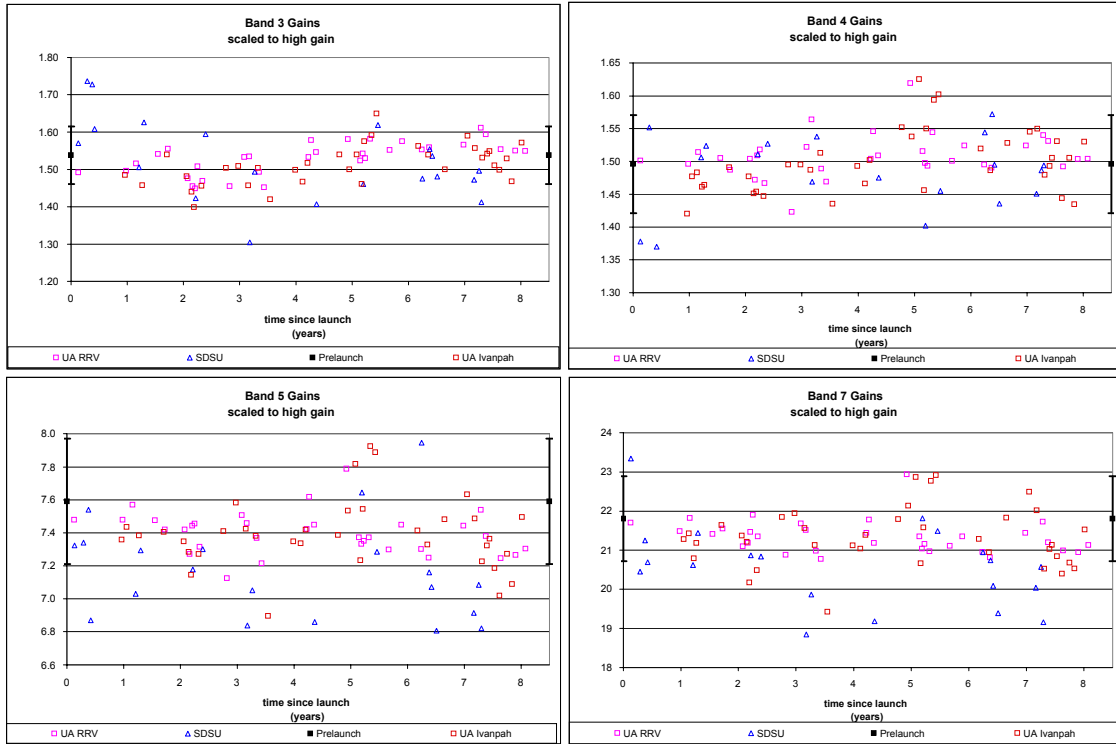


Figure 5. ETM+ vicarious calibration results from UA and SDSU. Both teams have been collecting ground truth regularly since launch.

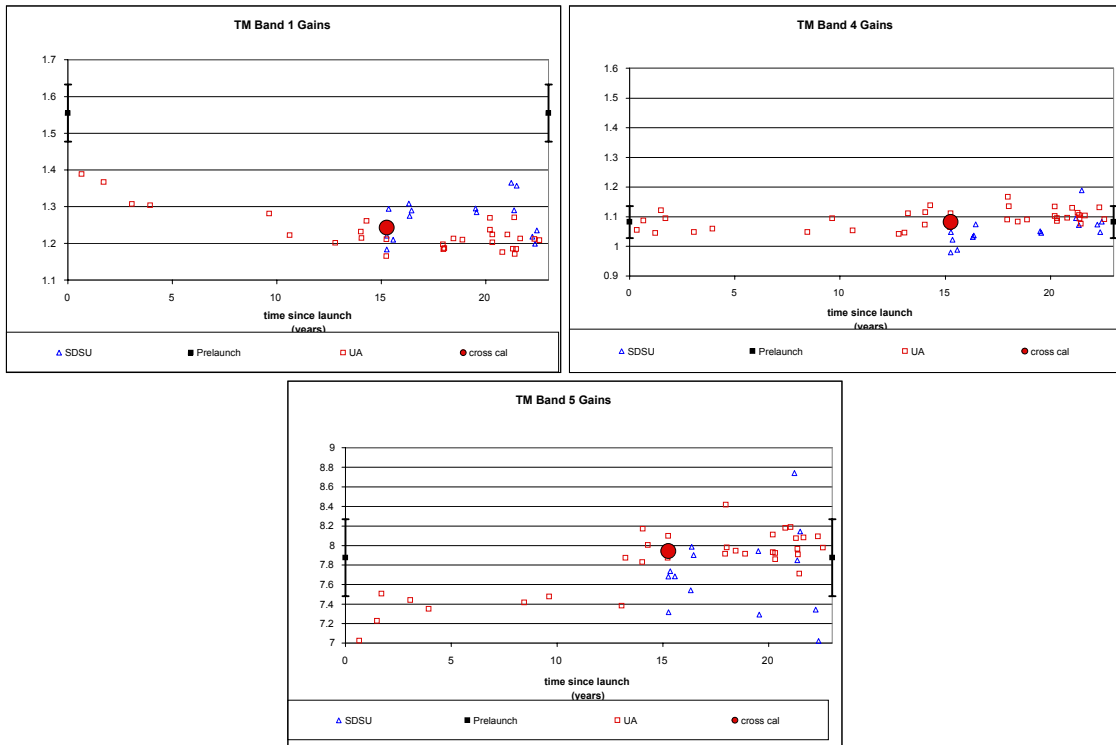


Figure 6. TM vicarious calibration results from UA and SDSU. UA was acquiring ground truth under TM sporadically throughout its lifetime, but SDSU only started taking ground truth after the spacecraft reverted to government control.

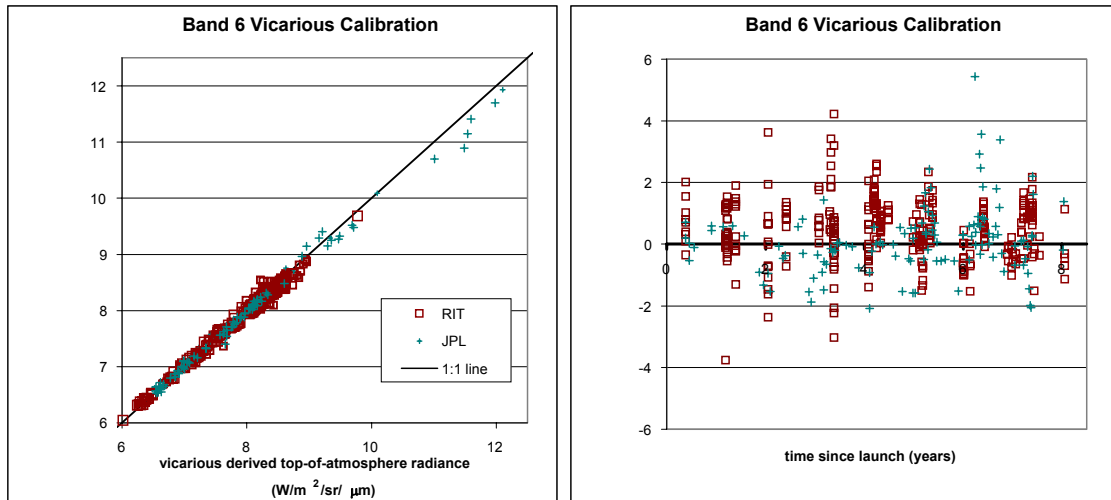


Figure 7. ETM+ Band 6 vicarious calibration results from JPL and RIT. On the left, the data are scattered about the 1:1 line, which is more evident in the residual error plot on the right. The highest radiances are from hot playas, while the water targets range from 6-10 W/m² sr μm. These data are corrected for the early offset error. Since that was corrected, there has been no indication of a calibration error.

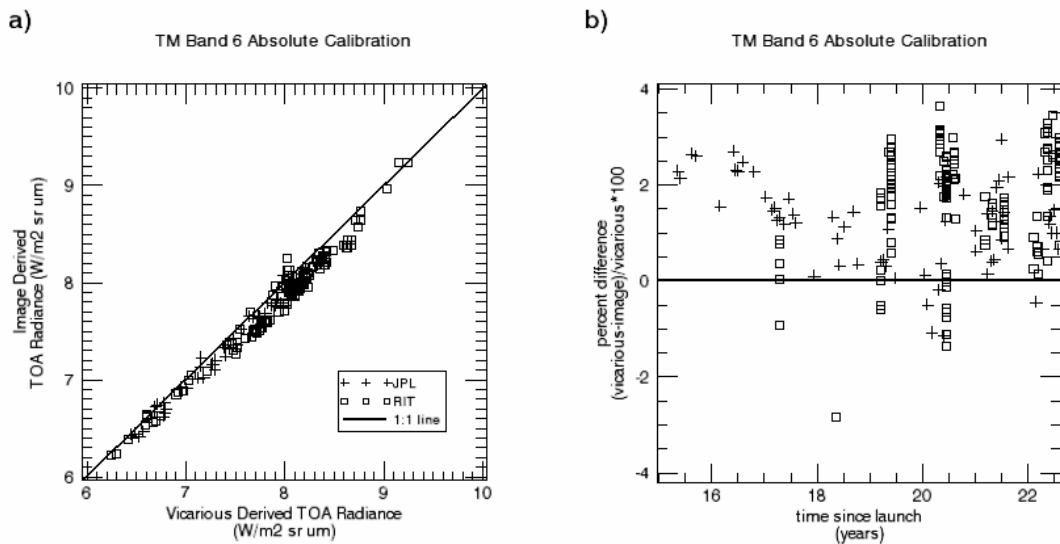


Figure 8. TM Band 6 vicarious calibration results from JPL and RIT. No playa data has been taken under Landsat-5, so the radiance range is much smaller. Vicarious efforts only began in earnest for TM in 2003, and only go as far back as 1999. The offset error, apparent in both plots, was being tracked for several years and was finally corrected for in the processing system in April 2007.

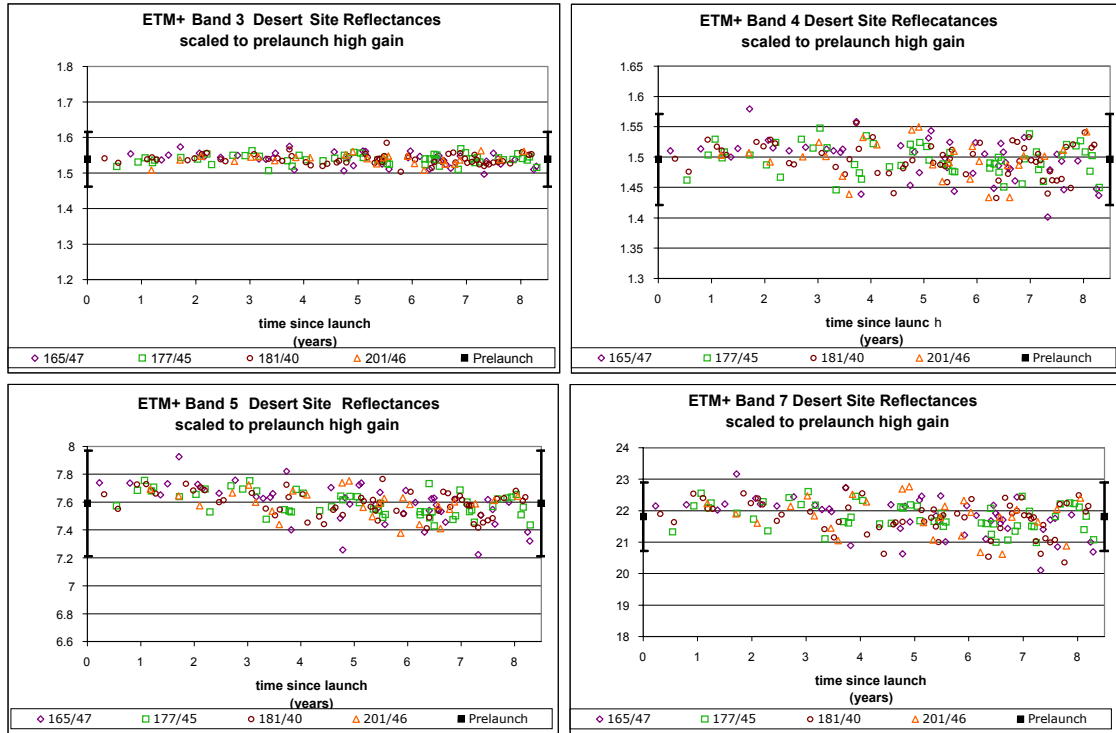


Figure 9. ETM+ derived gains for four sites in the Saharan and Arabian deserts. Each site's reflectance is trended separately and scaled to prelaunch gain to be put on the same scale as the other gain measurements. Also plotted are the prelaunch gains with the $\pm 5\%$ error bars.

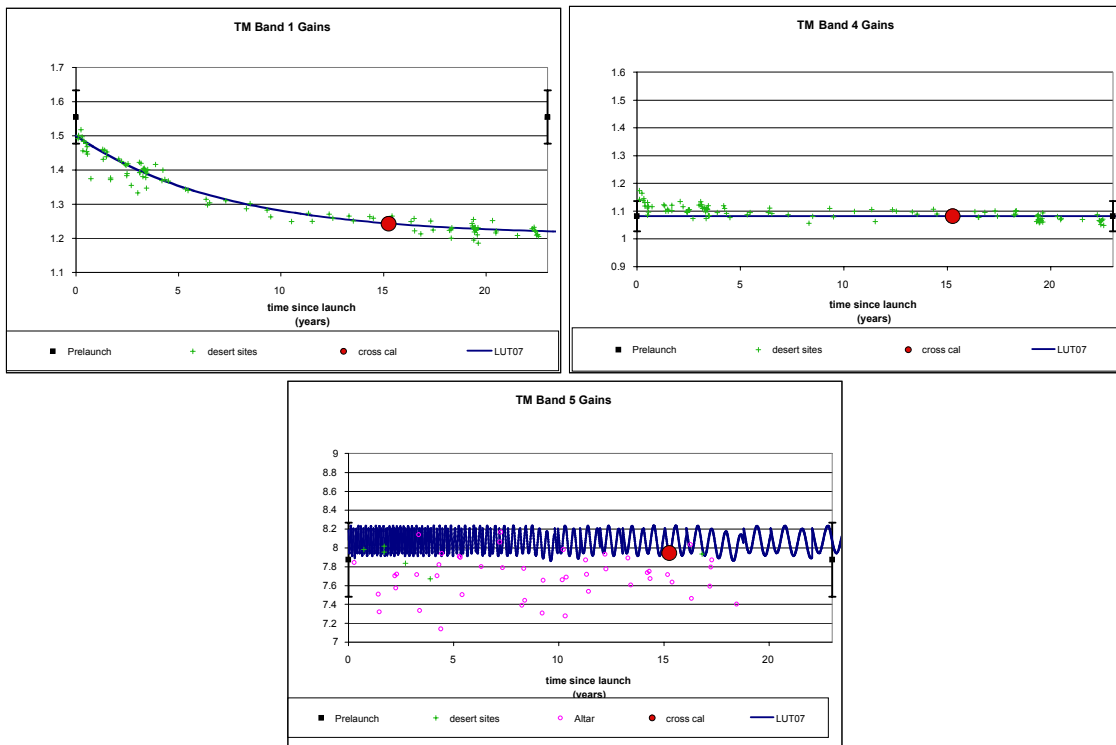


Figure 10. TM derived gains for desert sites; the Saharan site for bands 1 and 4, and the Altar site for band 5. The gain is actually raw DN scaled to the ETM+ cross-cal point. The new gain model is also plotted here; an exponential+constant model in band 1, a constant in bands 4 and 5. Band 5 is modified by the outgassing model to account for the change in gain due to the contamination build up.

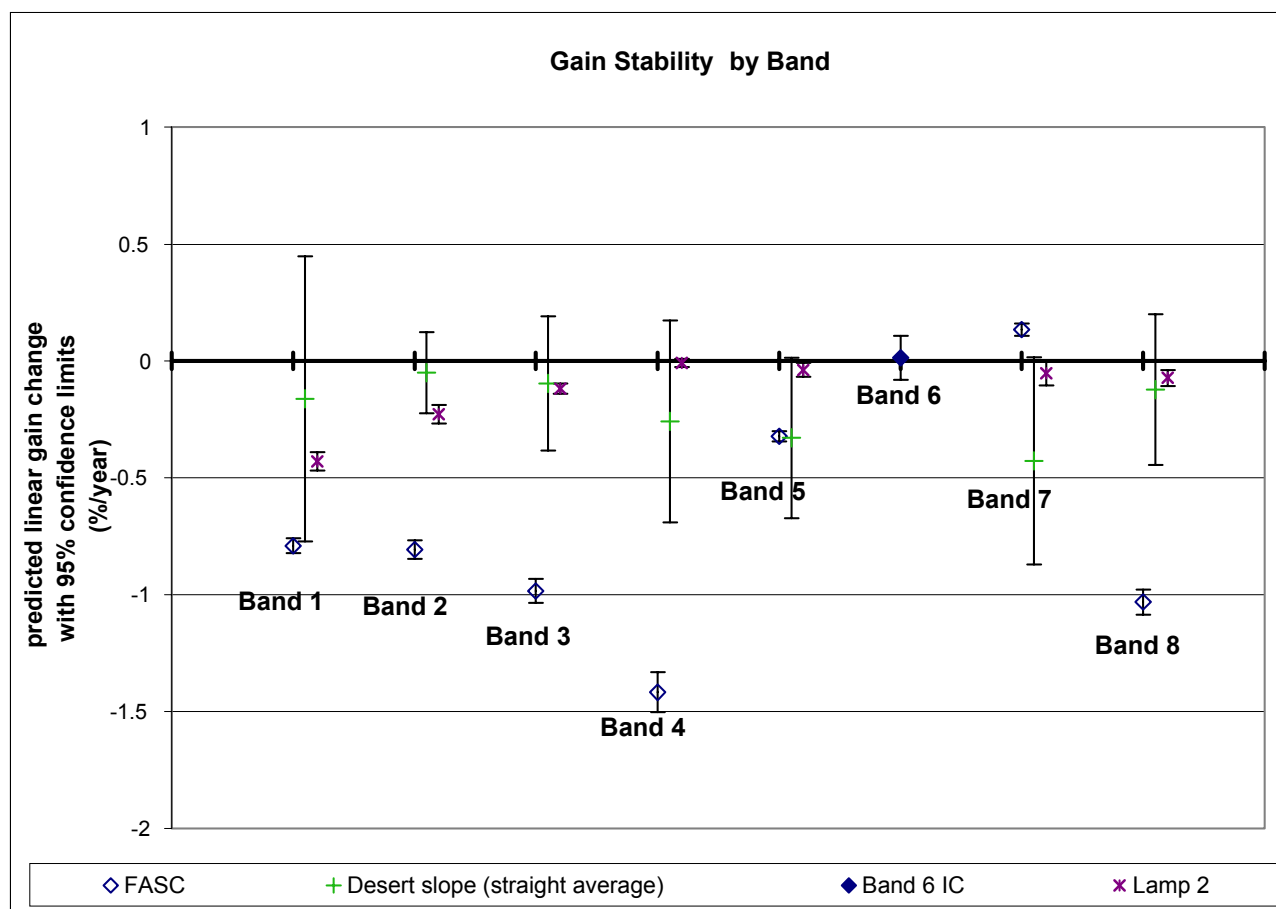


Figure 11. Estimated percent gain change per year for the various ETM+ calibrators. Error bars are the 95% confidence limits in the slope estimate. In the reflective bands, the FASC gain change is clearly different than the lamp 2 and the desert sites. The lamp 2 change is significant, but could be due to changes in the IC system. The desert sites slopes are not significantly different than zero, so indicate there is no change in gain. However, they do not preclude the small changes indicated by lamp 2.